

Chapter 6

Headwater Streets

Introduction

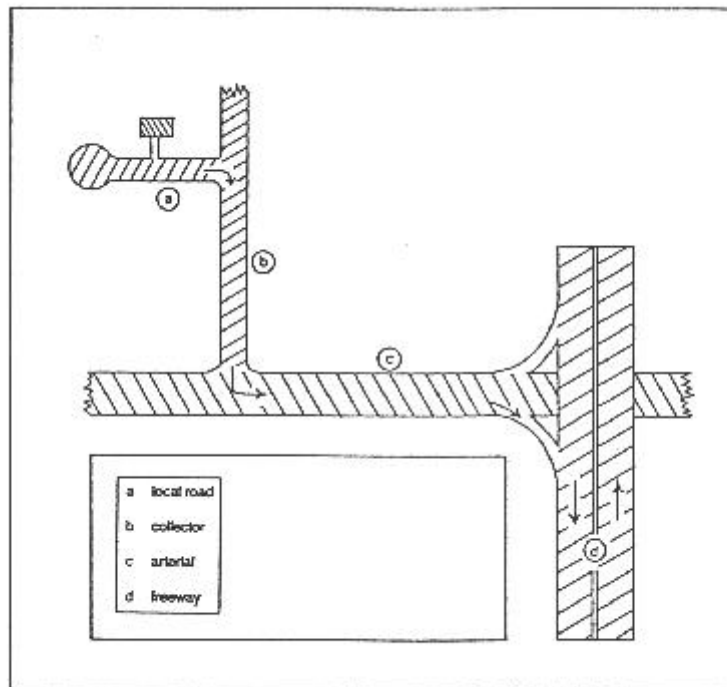
The greatest share of total impervious cover in most communities is from the roads, sidewalks, parking lots and driveways used to get us to where we work, live or shop. This reflects the strong influence that the car has in shaping the design of our communities. In this chapter, we examine techniques to reduce the impervious cover created by residential streets. The term “headwater streets” is used here to distinguish residential streets from the wider and more heavily travelled roads and

highways that are also a part of the urban landscape.

Some Street Geometry and Terminology

Road networks resemble stream systems in many respects. For example, they are connected in a hierarchial network that is quite similar to stream order. Small access streets generate the traffic that is routed to collector streets that in turn connect with arterial roads, that ultimately feed freeways (Fig. 33). Like streams, the capacity and width

FIGURE 33: THE HIERARCHY OF STREETS



Street systems are organized along a hierarchial network, with the smallest access streets feeding into collectors, which in turn connect to larger arterial streets and freeways.

of roads tend to increase in a downstream direction. And just like headwater streams, local streets comprise the majority of the road length of the entire road network in a community. Recent studies indicate that they represent between 50 and 65% of the length of the entire road network (Carroll County 1992).

The analogy with streams is not altogether perfect, however. The most notable difference is in the direction of flow. Runoff only travels in a downstream direction, whereas roads are designed for two way traffic of vehicles. This of course, introduces a safety problem—how to keep vehicles travelling in opposite directions from colliding with each other.

The traditional street classification system

Streets are classified according to the traffic volume they are expected to carry. Traffic volume is computed in a fairly simple manner. Each single family home generates a number of vehicle trips each day. As it happens, a typical single family home generates about ten trips every day. Thus, the expected traffic volume is simply the product of the average number of trips per residence and the number of residential units located along the street. This statistic, known as the *average daily traffic* or *ADT*, can be calculated for any street or road. For example, a residential access street that serves 15 homes would have an ADT of about 150.

Road designers use ADT to classify streets, and set road design standards. The hierarchical classification system assigns a street to one of four general categories, based on its ADT.

Thus, in ascending order of traffic volume, we have access streets, collector streets, arterial streets and freeways.

Access streets occupy the lowest rung in the street hierarchy. They conduct traffic between individual dwelling units and higher order streets (such as collectors, arterials and freeways) Also known as local roads, they generally handle no more than 500 to 1,000 ADT.

Collector streets are used to funnel traffic between smaller access streets and larger arterial roads. They act as the primary traffic route within a residential or commercial area, and can handle from 1,000 to 3,000 ADT.

Arterial streets provide a direct route for long distance travel to different parts of a community, and are fed by collector streets at controlled intersections. Arterial streets are designed for greater speed and volume and usually handle from 3,000 to 10,000 ADTs. Arterial streets may eventually feed into even larger freeways that allow for high speed travel from one region to the other.

Freeways can handle 30,000 or more trips each day, and are designed for limited and controlled access.

This chapter focuses exclusively on the design of smaller “headwater” streets (i.e., access and collectors) for two reasons. To begin with, most local communities only have authority to develop or modify design standards for headwater streets of a subdivision. Second, even if they had authority to modify the design

of larger arterials and freeways, there would be few opportunities to make these roads narrower (indeed, many larger road systems are continually widened to keep up with ever expanding traffic volumes).

Why are Residential Street So Wide?

The design standards that govern the geometry of roads are derived from two basic sources: the American Association of State Highway and Transportation Officials (AASHTO 1990) and the Institute of Transportation Engineers (ITE 1987, 1991). One of these sets of standards must be followed for any street or road project built with state or federal funds,

them without change for local roads. A summary of existing design standards is presented in a very condensed form in Table 33.

When it comes to residential access roads, the current AASHTO and ITE recommendations adopt a one-size-fits-all approach (Stabenfeldt 1995). For example, AASHTO only recognizes one basic design for residential access streets, that has a minimum pavement width of 26 feet, and 24 extra feet for the right of way. The ITE standards, which are less frequently used as the basis for residential street design, do allow for a greater range of widths, depending on terrain, housing density, and whether on-street parking will be

TABLE 33: CONDENSED SUMMARY OF NATIONAL DESIGN STANDARDS FOR RESIDENTIAL STREETS

DESIGN CRITERIA	AASHTO	ITE	HEADWATER STREETS
Residential Street Categories	1	3, depending on land use density	4, depending on ADT
Minimum Street Width	26 ft min.	22–27 ft >2 du 28–34 ft 2–6 du 36 ft < 6 du	16 ft (>100 ADT) 20 ft (100–500 ADT) 26 ft (500–3,000 ADT) 32 ft (>6 du/ac)
Additional Right of Way	24 ft	24 ft	8 to 16 ft
Design Speed, Level Terrain	30 mph	30 mph	15 to 25 mph
Curb and Gutter	generally required	generally required	not required on collectors
Cul-de-sac Radii	30 ft	40 ft	30 ft
Turning Radii in Cul-de-sac	20 ft	25 ft	17 ft

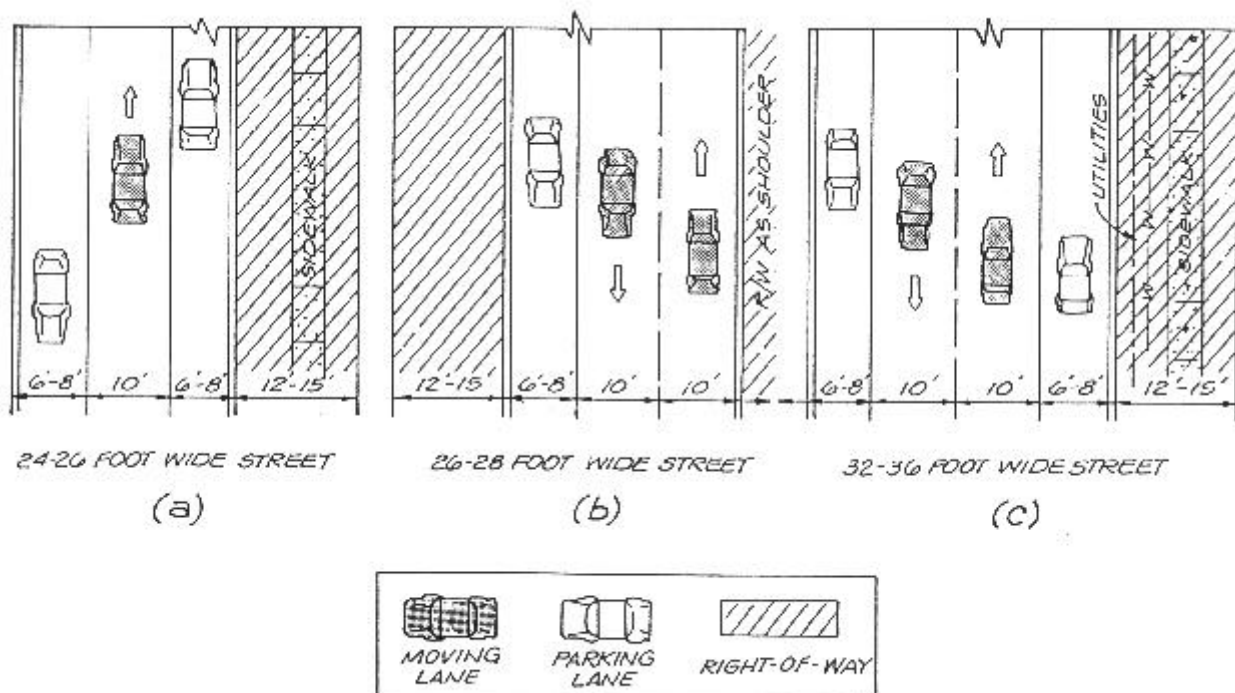
provided on one or both sides of the street. Thus, under the ITE standards, pavement width can range from 22 to 36 feet, with most streets between 28 and 34 feet. In practical terms, street widths are determined by the number of parking and moving lanes provided (Figure 34):

- 9 three eight foot lanes, devoted to moving or parking = 24 feet
- 9 one ten foot moving lane, plus two eight foot parking lanes = 26 feet
- 9 two ten foot moving lanes, plus one eight foot parking lane = 28 feet
- 9 two ten foot moving lanes, plus two eight foot parking lanes = 36 feet

mind. First, wide residential streets are designed to promote relatively rapid traffic flow, at an average speed limit of 30 mph on level or rolling terrain. The wider streets and better sight distances, however, encourage many drivers to exceed even this relatively high speed. High speeds, however, are not desirable in residential neighborhoods. One way to force drivers to slow down is to reduce street width.

Second, street width is generally determined by the planned function of the street, rather than the actual traffic capacity it experiences. As a consequence, street width is fixed, regardless of whether it serves 10 homes or

FIGURE 34: PARKING AND MOVING LANES IN RESIDENTIAL STREETS



The width of residential streets is determined by the number and width of moving and parking lanes provided. In headwater streets, a parking and moving lane are shared, thereby reducing street width.

100 homes. To put this into perspective, consider the relationship between the number of dwelling units and the traffic they generate (Table 34). A residential street serving ten homes can be expected to handle about 100 cars each day, which equates to an average of roughly 15 minutes between each car trip (6 minutes during the peak hour). A second street serving 100 homes will typically handle a thousand car trips each day, with one car trip generated every 90 seconds (about 30 seconds during the peak hour). In the first case, vehicles can share a common moving lane since one vehicle can pull into a parking lane to allow another vehicle to pass. This rather minor inconvenience does not occur very often when the number of homes served by the street is small (see Table 34). Shared moving lanes become a major inconvenience,

and a possible safety hazard, however, once a street serves more than 50 dwelling units.

Third, streets are often utilized as a spillover parking area in residential neighborhoods, with one or more on-street parking lanes being provided. Residential parking demand has grown sharply over the last decade in response to ever increasing trends in car ownership. For example, over a third of all families in the US now own two or more cars (ULI 1990). Consequently, two to three parking spaces must usually be supplied per dwelling unit to accommodate the future parking needs of residents and their visitors. In large lot developments, however, on-street parking lanes creates a surplus of unused parking areas.

TABLE 34: RELATIONSHIP BETWEEN NUMBER OF DWELLING UNITS, TRAFFIC GENERATION, AND RESIDENTIAL CONGESTION

No. of SF Homes	Average Daily Trips	Peak Trips Per Hour	Minutes between cars (average)	Minutes between cars (peak)
5	50	5	30	12
10	100	10	15	6
25	250	25	6	4
50	500	50	3	1.5
75	750	75	2	45 secs
100	1,000	100	1.5	35 secs
150	1,500	150	1	20 secs
300	3,000	300	30 secs	10 secs

Many residential streets carry relatively few vehicles each day. For example, streets serving less than 25 homes are so lightly travelled each day (and during peak hours) that shared parking and moving lanes make sense.

The Headwater Street Alternative

The design of headwater streets is directly linked to the traffic and parking demand generated by the homes that are served. In general, streets are designed to the narrowest width capable of fully meeting the traffic and parking demand. A revised classification system for headwater streets is presented in Table 35, where street width declines with decreasing ADT. The classification system represents a composite of innovative residential street standards drawn from several communities around the country. Five residential street categories are defined based on traffic and parking demand. They are:

Lane: serves less than 15 homes with a density of 2 dwelling units per acre or more. This low speed street is only 16 feet wide, with an additional 8 to 16 ft. right-of-way. Parking demand is met by driveways or grass shoulders, and drainage is typically provided by grassed channels.

Access: these streets serve 15 to 50 homes, and are only 20 to 22 feet in width (either two moving lanes, or a parking lane and a shared moving lane). The right-of-way may extend 8 to 24 feet, depending on whether a grass channel or curb/gutters are used for drainage. A sidewalk is located on one side of the street.

Standard street: this street category handles traffic from 50 to 100 homes, and is 26 feet wide, thereby allowing for one moving lane and two parking lanes (one of which doubles as a moving lane most of the time). Drainage is usually provided by curb and gutters.

Dense street: a wider street (32 to 34 feet) is often needed when housing densities exceed four dwelling units/acre in order to meet residential parking demand. Parking lanes are provided on both sides of the street, although one or both lanes can be eliminated if a street section is more than 200 feet away from the nearest residence (i.e., hourglass streets). The dense street often will have curb and gutter, and can have sidewalks on one or both sides of the street.

Collector: the primary function of this street category is to funnel traffic from neighborhoods to arterial streets, and because of the high traffic level (1,000 to 3,000 ADT), no frontage lots are allowed. The typical width is 22 feet which consists of two moving lanes (with grass shoulders for emergency parking) or 28 feet if a spillover parking lane is needed.

The headwater street classification system represents the minimum width that can probably be achieved without compromising safety or traffic flow (Fig. 35). Communities will need to modify it to reflect their unique street terminology, trip generation rates, snow storage, utility and pedestrian access requirements.

Residential Street Features

Residential streets do more than just carry cars. They also serve as a major corridor for utilities and pedestrian movement in a community. As a result, most communities require a minimum 12 to 15 foot wide *right of way* on each side of the street. Underground lines provide water, sewer, telephone, gas or

TABLE 35: CONDENSED SUMMARY OF DESIGN STANDARDS FOR FIVE CATEGORIES OF HEADWATER STREETS

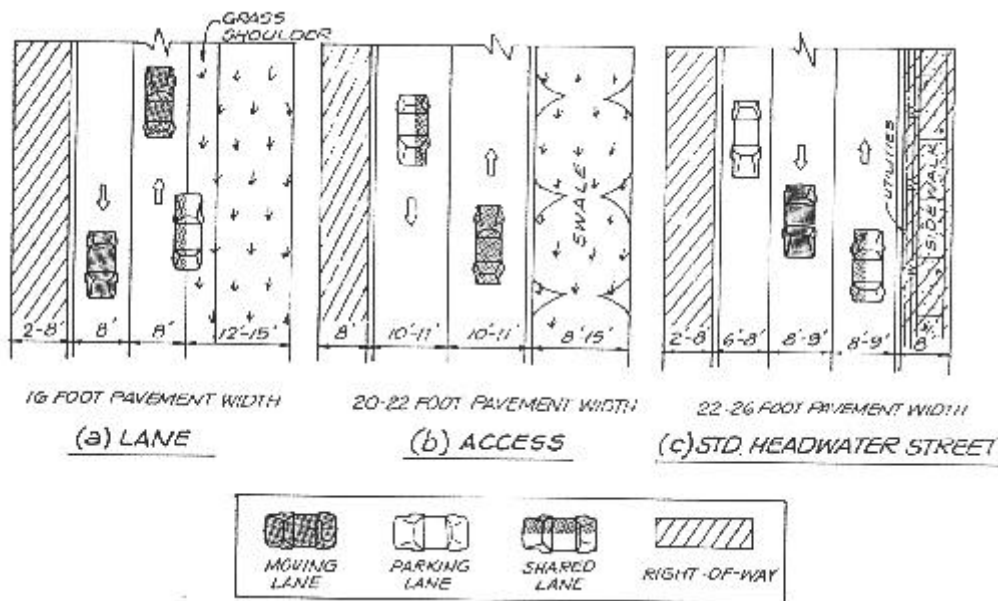
Design Factor	Lane	Access	Standard Street	Dense Street	Collector
ADT	less than 100	100 to 500	500-1,000	100-1,000 at 4 du/ac	1,000 to 3,000
Width	16	20	26	32	22 to 28
Extra ROW	8 to 16 ft.*	8 to 24 ft.*	20 ft.	20 ft.	22 to 28 ft.
Off-Street Parking	private driveways	private driveways	private driveways	multi-family parking lots	none
On-Street Parking	None	one-lane	one-lane	two-lane	emergency shoulders
Drainage	Swale	Swale or curb/gutter	curb/gutter	curb/gutter	Swale or Shoulder
Design Speed	15 mph (max)	20 mph	25 mph	25 mph	25 mph
Sidewalks	none	one-side	one or two sides	two sides	one side
Frontage Lots	yes	yes	yes	yes	no
<p>The terms used to classify the five kinds of headwater streets are illustrative only, and many communities may want to use other terms. The dense street refers to a street section that serves 4/du/ac or more that may require on-street parking or multi-family parking lots to meet parking demand.</p> <p><i>*higher right of way length is needed for grass channels and grass roadway shoulder.</i></p>					

electricity service to each home within this protected easement. In addition, sidewalks and street trees are located inside the right of way, usually on both sides of the street. In northern climates, the right of way is also used to store excess snow during the winter months.

The right-of-way is also the primary corridor for moving stormwater runoff away from a development. Runoff is conveyed along the street network in one of two ways, either (a) in

an open *grass channel* located in the right of way or (b) in an *enclosed storm drain* located under the street or right of way. Storm drains are fed by a system of *curb and gutters* that channels street runoff into a pipe inlet. Open channels and storm drains are both sized to handle large runoff volumes, and typically have a capacity to carry the runoff from a ten year design rainfall event.

FIGURE 35: COMPARISON OF HEADWATER STREET WIDTHS



Several options for sharing parking and moving lanes are at the heart of the headwater street concept.

The use of an open channel or storm drain in a particular street is determined by a number of factors, such as drainage area, slope, length, housing density, and street type. Open channels can be used on smaller streets, but at some point, runoff velocities become too erosive to be safely handled in an earthen channel, and they must be enclosed in a storm drain. This limit, known as the *critical erosive velocity*, is typically around 4 to 5 feet per second. A channels' maximum velocity is generally defined and computed using the peak discharge rate under the two year design storm event.

Open channels can have many stream protection benefits. For example, stormwater pollutants are filtered through grass or soil as they pass through the channel. The lack of a curb eliminates a major trap of airborne pollutants. In addition, runoff can infiltrate into

the soil during small and moderate storm events. Performance monitoring, however, has shown that drainage channels only realize these benefits under ideal conditions (e.g., low slope, sandy soils, dense grass cover, long channel lengths, etc.—Dorman et al. 1989, Harper 1988, Yousef et al. 1985). When these conditions are not met, drainage channels can have a low or even negative removal capability for many pollutants (MWCOG 1983, Dorman et al. 1989).

Only recently have engineers recognized the value of designing open channels explicitly for pollutant removal during small and moderate-sized runoff events (Seattle METRO 1992, Claytor and Schueler 1995). Channel dimensions are intentionally set to promote longer residence times and/or to promote greater runoff infiltration. Depending on the depth to the water table, they are known as

either *grass channels*, *dry swales* or *wet swales*. (Fig. 36). Checkdams, underdrains, stone inlets, prepared soil mixes and landscaping are also used to enhance the pollutant removal capability of swales. The use of grass channels or swales along headwater streets is an economical and effective element of a BMP system, as long as the critical velocity is not exceeded. In addition, open channels in residential areas must be designed to prevent standing water, to ensure that mowing and snow removal operations are convenient, and to avoid odors, mosquitos or other nuisances associated with stagnant water.

Residential parking demand can be met by on-street parking lanes, private driveways or lots, or a combination of the two. Private driveways can usually meet the entire parking demand in larger-lot developments. Eventually, however, a threshold is crossed where parking demand can no longer be met solely by private driveways. Typically, this transition to on-street parking lanes occurs at housing densities of about 3 to 4 dwelling units per acre (Arendt 1994).

Another residential street feature involves *turnarounds*. If an access street has a dead end, provisions must be made to allow for vehicles to conveniently turnaround. The most common approach utilizes a circular turnaround known as a *cul-de-sac*. Traditional cul-de-sac design were based on the turning radii needed for large vehicles—fire trucks, garbage trucks, moving vans, school buses, and resulted in diameters of 80 to 100 feet or more (Reed 1991). As time as gone by, many communities recognize that the diameter of cul-de-sac is excessive (ULI 1990). A better alternative on

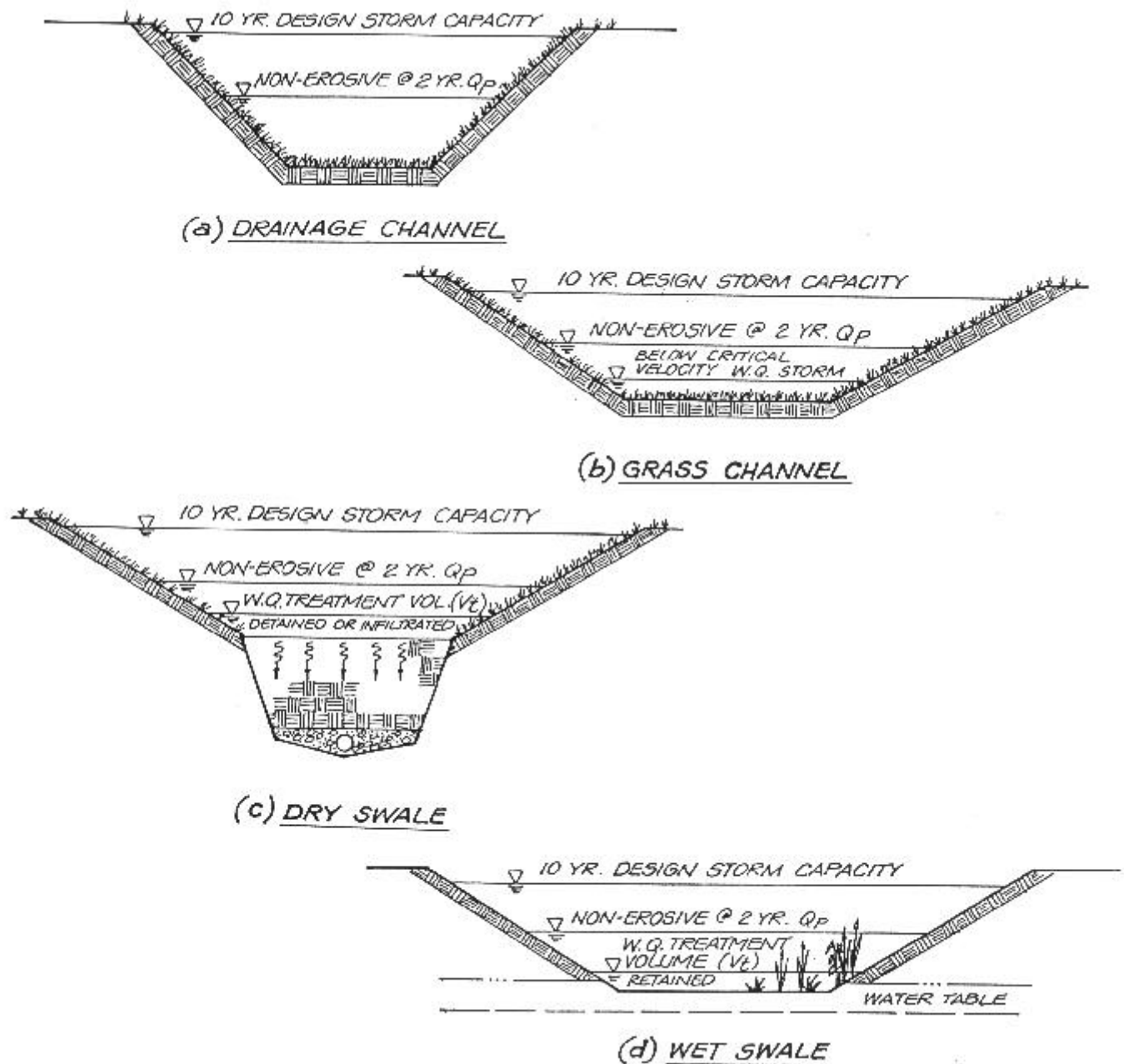
headwater streets are T-shaped or hammerhead turnarounds, which create less impervious cover.

Pollutant Generation From Streets

Streets are a key source area in the urban landscape where stormwater pollutants accumulate. Pollutants can take a wide number of pathways before they are trapped on the street surface (Fig. 36). While the deposition of pollutants from the atmosphere by dryfall and wetfall remains the primary pathway, a street has many other pollutants pathways. For example, trace metals such as cadmium, copper and zinc are often the product of gradual wear of tires or brakepads of cars as they pass over the street. The contribution of metals from this pathway can be regionally significant; the Santa Clara NPS Program (1994) reported that over 50% of the copper, cadmium and zinc could be attributed to this source. Cars are also thought to be an important source of hydrocarbons, through car emissions, leaks, or spills.

In northern climates, sand, salts or other deicing agents are applied for road traction and can be a major seasonal pollutant source on street surfaces. Snow plowed to the curb or the right-of-way can also become a pollutant storage area. Chemicals, grit and litter accumulate in the road-side snowpack over an entire winter, and when snow melts in the spring, pollutant concentrations often exceed

FIGURE 36: OPEN CHANNEL OPTIONS FOR RESIDENTIAL STREETS



Open channels can be designed in one of four ways—as either (a) a drainage channel, (b) a grassed channel, (c) a dry swale, or (d) a wet swale. All open channels are typically designed to convey the ten year design storm, and prevent critical erosive velocities during the two year design storm. The grass channel is designed to achieve a critical velocity during a water quality design storm. The dry swale is designed to capture and treat the entire water quality volume in the swale. The same is true for the wet swale, except that the storage is provided by a pool of water, due to the presence of a high water table.

those recorded in warmer months (Oberts 1994).

One poorly understood pathway is the breakdown of the pavement surface itself. Little research has been performed to determine whether asphaltic compounds are released shortly after resurfacing, gradually over time, or not at all.

Pollutant loads generally increase as average daily traffic volume increase. Runoff monitoring by the Federal Highway Administration indicates that pollutant concentrations are greatest along urban interstate highways with a traffic volume

greater than 30,000 ADT (Table 36). Rural highways are reported to have pollutant levels similar to those measured in residential and commercial runoff (which are dominated by streets and parking lots).

Lastly, the very nature of the street itself traps pollutants that blow in from outside areas. Even the modest vertical break of a curb shelters airborne pollutants that may have blown in by the wind. Thus, dust, pollen, leaves, grass clippings, and organic matter can be trapped by the curb, where they remain until they are washed into the stormdrain system. Some idea of the trapping potential of curbs and gutters is found in the data of

TABLE 36: COMPARISON OF HIGHWAY AND URBAN RUNOFF POLLUTANT CONCENTRATION DATA (ADAPTED FROM FHWA 1990 AND US EPA 1983)

Median Pollutant Concentration	Highway (a) > 30,000 ADT	Highway (a) < 30,000 ADT	NURP Runoff Data (b)
TSS (mg/l)	142	41	100
COD	114	49	65
Nitrate-N	0.76	0.46	0.82
TKN	1.83	0.87	0.68
Total Phosphorus	0.40	0.16	0.33
Copper (ug/l)	54	22	34
Lead	400	80	140
Zinc	329	80	160
Sources (a) FHWA runoff data N=993, (b) NURP Runoff data N=2300, includes primarily residential, commercial and mixed use sites that include roads and parking areas. ADT= Average Daily Traffic volume			

Bannerman (1994). Figure 37 shows the comparative concentration of coliform bacteria from various urban sources. Bacterial concentrations were one to two orders of magnitude higher in the street curbs compared to parking lots or roof runoff. Residential streets, in particular, were discovered to have the highest concentrations of harmful bacteria.

Once pollutants accumulate on a street surface, their delivery to the stream system is almost assured (Fig. 38). The crown of the street directs runoff over to the curb, where it is soon routed to a storm drain inlets. Since the storm drain network is designed to be self-cleansing, pollutants have a very high probability of reaching the stream without modification.

FIGURE 37: BACTERIA LEVELS MEASURED FROM VARIOUS URBAN SOURCE AREAS (BANNERMAN 1994)

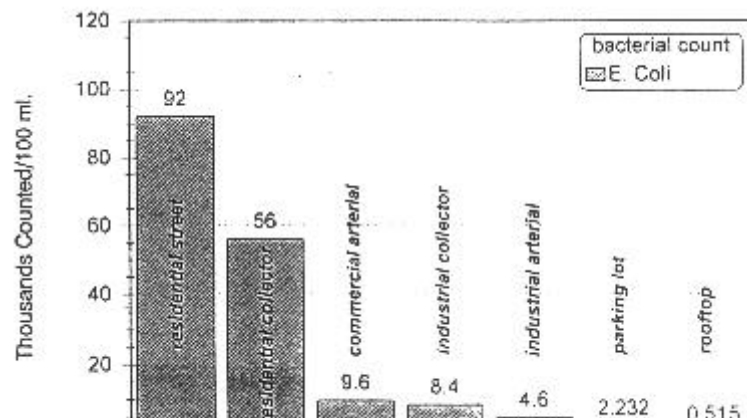
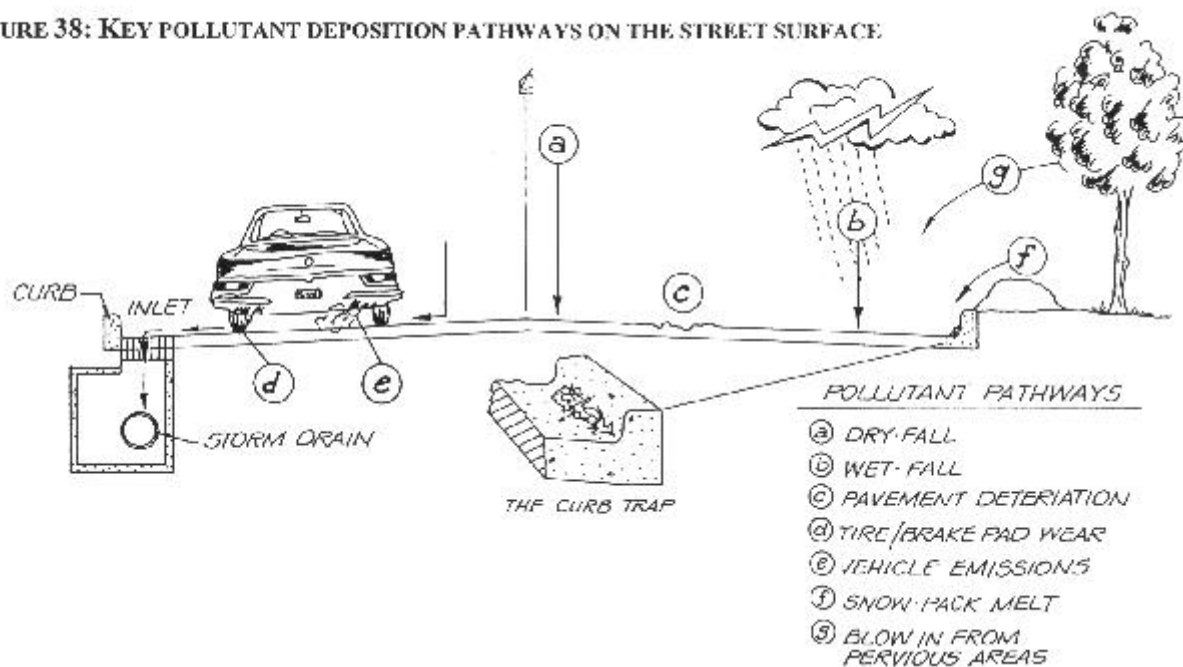


FIGURE 38: KEY POLLUTANT DEPOSITION PATHWAYS ON THE STREET SURFACE



Curbs provide an effective trap for airborne pollutants, snow, vehicle emissions; as well as a very efficient means for washing pollutants into the storm drain systems.

General Model of Residential Street Impervious Cover

The amount of impervious cover created by a residential street system can be analyzed using a simple model. Total impervious cover (Ic) is the sum of the impervious cover produced by five residential street features:

$$Ic = R + Rw + S + T + D$$

where:

- R = road length
- Rw = road width
- S = sidewalks
- T = turnarounds, and
- D = driveways

The specific amount of impervious cover created by each individual residential street feature is easily computed, based on their average length and width, which is governed by the prevailing subdivision codes of a community. For example:

Road length (R). The minimum distance of the road for a given zoning category is computed as:

$$R = \{(\text{Number of Dwelling Units}) (\text{Average Feet of Frontage Required})\} / 2$$

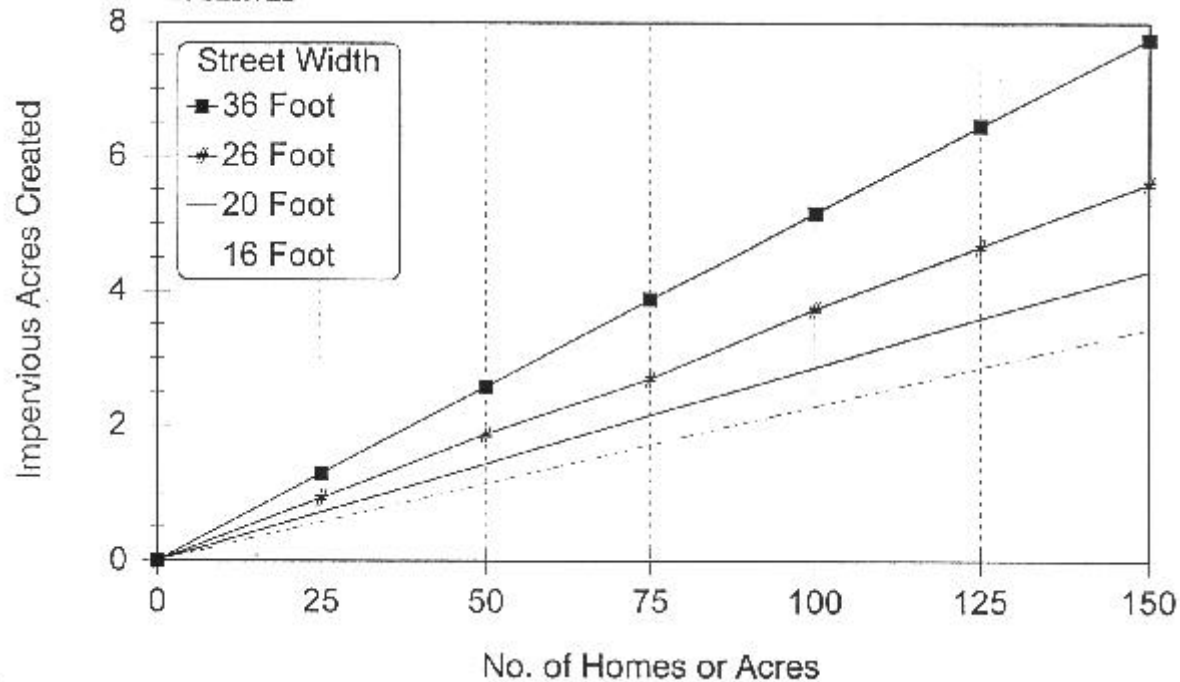
As the equation shows, the only significant way to reduce road length is to lower the minimum frontage requirement, which is typically set by local subdivision codes. Communities that allow designers flexibility in this key lot dimension to promote stream protection cluster can greatly reduce the amount of impervious cover created, regardless of the road width. As was discussed in Chapter

4, stream protection cluster can reduce the length of the road network by as much as 50%.

Road width (Rw). Once the minimum length of the road network is established, the next key variable to address is road width. If the traditional residential street width of 36 feet is used as a baseline, we can analyze the impact of narrower headwater streets on the creation of impervious cover. This relationship is graphically displayed in Figure 39, which shows the number of impervious acres created as a function of the number of dwelling units and street width, for single family homes situated on one-acre lots. As an example, consider a subdivision containing 50 homes. A 36-foot-wide street system creates about 2.5 acres of impervious cover, while a 26-foot street creates only 1.8 acres of impervious cover, or a savings of 28%. The use of even narrower headwater streets (16 or 20 feet) produce even greater savings.

Sidewalks (S). The next residential street variable are sidewalks used for pedestrian movement. Most communities require that they be installed on one or both sides of a street. The minimum width of sidewalks is four feet (which allows a wheelchair adequate passage, under the requirements of the Americans with Disabilities Act), but some communities often require that they be five or even six feet wide. Based on these parameters, the calculation of impervious cover created by sidewalks can be computed in a straight forward manner:

FIGURE 39: IMPERVIOUS COVER CREATED AS A FUNCTION OF ROAD WIDTH AND NUMBER OF DWELLING UNITS SERVED



The model of residential street impervious cover indicates that significant reductions in impervious cover can be achieved through narrower streets.

$$S = (S_n) (R) (S_w)$$

where:

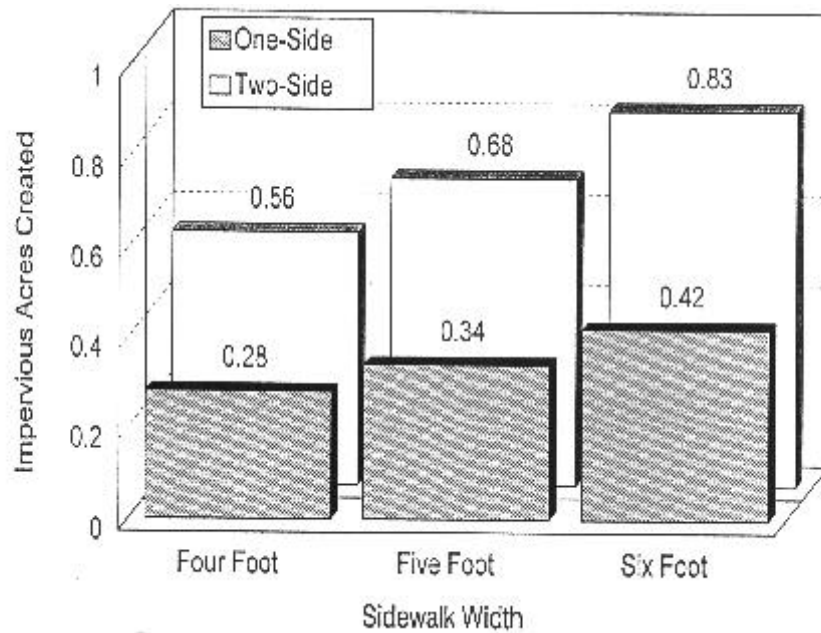
S_n = local sidewalk requirements (0, 1 or 2 sides).

R = road length (linear ft.)

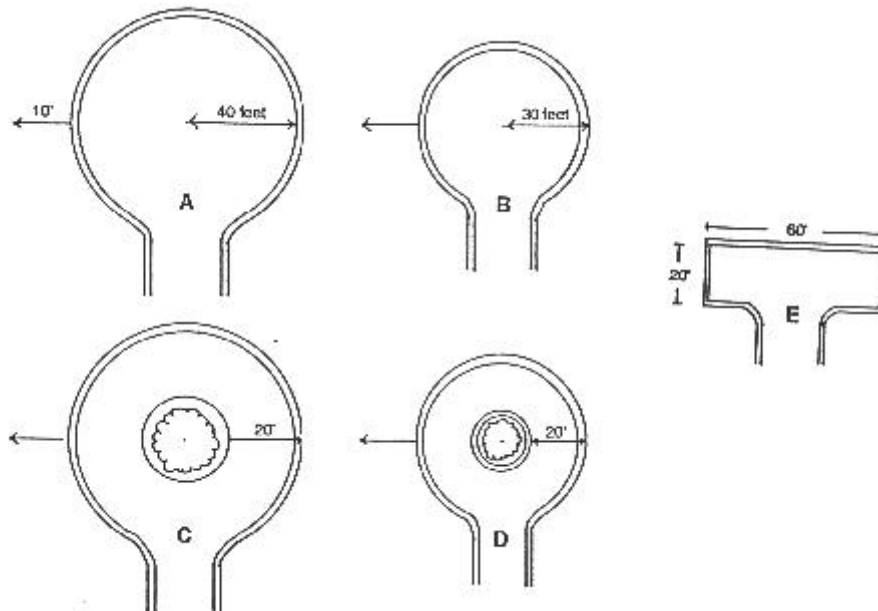
S_w = local sidewalk width (4, 5 or 6 ft.)

Using the same example of a 50 acre single family home subdivision, we can then determine the amount of impervious cover created by sidewalks, using different assumptions about local requirements (Fig. 40). The acreage of impervious cover can be seen to range from none to slightly less than one acre (0.83 acres).

Turnarounds (T). Dead end streets in residential subdivisions are usually required to have an acceptable option for vehicles to turnaround, with the circular cul-de-sac being the most common. A range of five different turnaround options are depicted in Figure 41. In each case, they provide a minimum internal turning radius of 17 to 20 feet to accommodate the larger vehicles. The sharp differences in the amount of impervious cover produced by each turnaround option is shown

FIGURE 40: IMPERVIOUS COVER CREATED BY TYPICAL RESIDENTIAL SIDEWALK STANDARDS

Subdivision requirements on both the width and number of sidewalks can create almost an acre of impervious cover in a 50 acre residential subdivision.

FIGURE 41: FIVE TURNAROUND OPTIONS AT THE END OF A RESIDENTIAL STREET

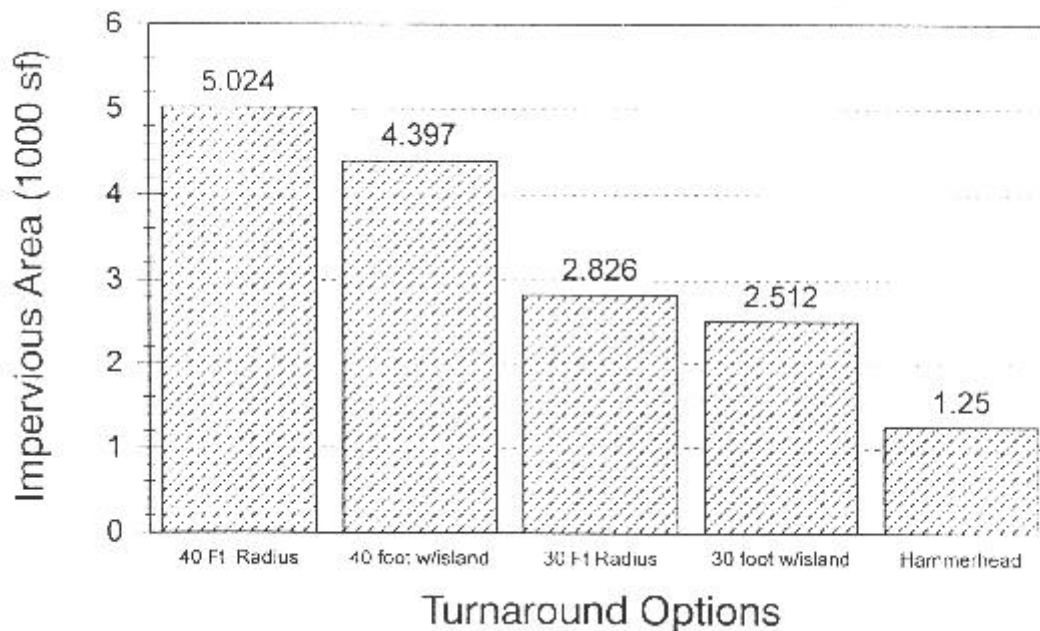
Five options for turnarounds include (a) 40 foot radius circle (b) a 30 foot radius circle, (c) a 40 foot circle with pervious donut, (d) a 30 foot radius circle with pervious donut and (e) a 60 by 20 foot "T"—shaped or hammerhead.

in Figure 42. It is clearly evident that large cul-de-sac radii create needless impervious cover, even if a landscaped “donut” is installed in the center (see Figure 41). Approximately 50% less impervious cover is created simply by dropping the radius from 40 feet to 30 feet. An even greater reduction occurs when T-shaped or “hammerhead” turnarounds are used. In hammerheads, a vehicle must make a required three-point turn to completely reverse direction, compared to a two point turn (in 30 foot radius cul-de-sacs).

Driveways (D). The last residential street feature that creates impervious cover are private driveways. Most communities require a standard width of 20 feet for the driveway (with a slightly greater apron width, where the

driveway meets the street). A driveway this wide allows two cars to be easily parked side by side. Deriving the average length of the driveway is a more complicated affair. Most communities specify that homes must be set back a fixed distance from the street right-of-way, depending on the residential zoning category. This requirement is sometimes expressed as a fixed length (40 or 60 feet), or a percentage of the lot depth (e.g., the home must be set back at least 40% of the distance between the front yard and backyard boundary). Since the driveway needs to extend from the street to the home, its length is fundamentally determined by the setback requirement. Thus, if the setback is 60 feet, the length of the driveway will be at least 60 feet plus the 12 or 15 feet of right-of-way from the street (for a total of 72–75 feet).

FIGURE 42: IMPERVIOUS COVER CREATED BY EACH TURNAROUND OPTION



The greatest impervious reduction is achieved using either a hammerhead, or by reducing the radius of a circular turnaround. Donuts have a minor effect on the amount of impervious cover created.

The last variable that we must define before we can compute driveway impervious area is the total number of driveways needed per linear foot of street (N). This is computed simply as:

$$N = R / (Fd/2)$$

where:

R = road length (linear feet)

Fd = average frontage distance in feet.

which allows us to compute the impervious cover associated as driveways (D) as:

$$D = (N) (Dl)(Dw)$$

where:

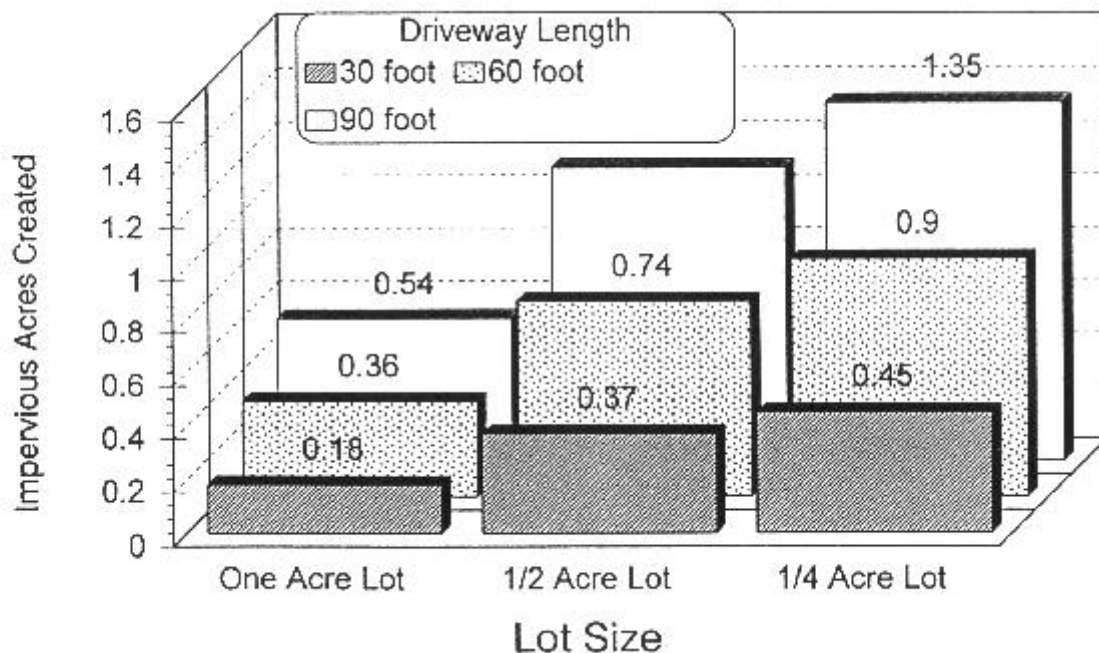
N = number of driveways

Dl = average driveway length = front yard setback

Dw = driveway width = 20 feet, but can be 12 feet in rural areas.

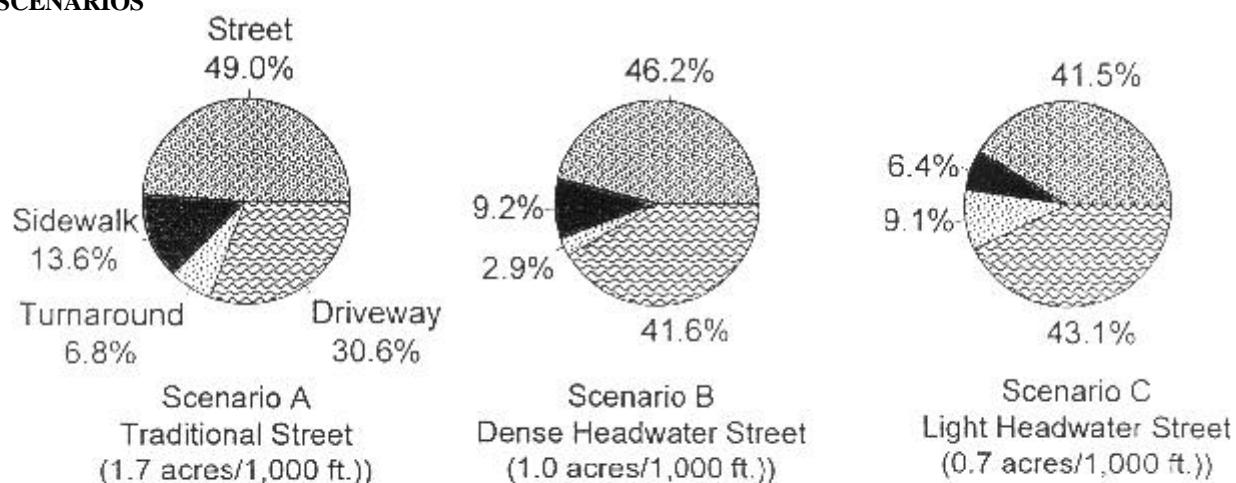
Driveways contribute a major share of impervious cover in residential streets. Using the 50-acre single family home subdivision example presented earlier, anywhere from 1.0 to 1.5 acres of impervious cover can be created solely by driveways. Driveways tend to create more impervious cover when lot size decreases (and a greater number of individual driveways are needed (Fig. 43). The strong influence of driveway length on the creation of impervious cover is also evident in the figure. It should be noted that after about 40 feet, a driveway can fully meet the parking demand for most homes, and additional length only functions to connect the street to the home.

FIGURE 43: DRIVEWAY IMPERVIOUS COVER AS A FUNCTION OF LENGTH AND LOT SIZE



Driveways contribute a surprising amount of impervious cover in the landscape. The amount increases as driveway lengths become greater (due to front yard setbacks) or housing density increases.

FIGURE 44: IMPERVIOUS COVER CREATED UNDER THREE RESIDENTIAL STREET DESIGN SCENARIOS



Residential Street Features

The residential street model is useful in analyzing the effect of local street standards on the creation of impervious cover. This example shows the difference between the most generous street standards, and the proposed headwater street standards.

The simple model presented above has great value in identifying the best opportunities to reduce impervious cover created by residential streets. For example, consider the case of a simple 1,000 foot dead-end street that serves single family homes situated on one-acre lots (Fig. 44). Using the model, we can see the relative share of impervious cover created by each of the five residential street features under traditional subdivision design standards using the following assumptions:

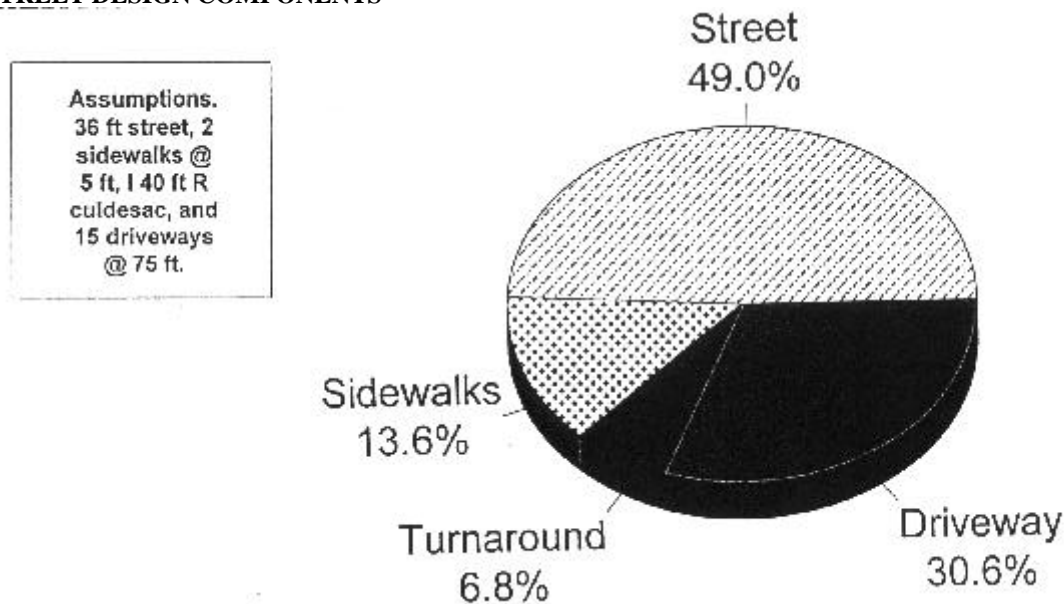
- R = 1,000 feet
- Rw = 36 feet
- S = 5 feet wide, both sides of the street
- T = one 40 foot radius cul-de-sac.
- D = 15 driveways that average 75 feet in length.

The total amount of impervious cover created under this scenario is about 1.7 acres (Fig. 45). The value of alternative headwater street design scenarios can then be assessed by modifying design assumptions, such as shown below.

	Scenario A: Headwater Streets	Scenario B: Headwater Streets and ½ acre cluster
R	1,000	500
Rw	20 feet	26 feet
S	4 foot, one-side	4 foot, one side
T	hammerhead	30 ft radius cul-de-sac
D	15 @ 60 feet	15 @ 45 feet

The cumulative impact of these measures results in a 40% (scenario A) or 60% (scenario B) reduction in impervious area.

FIGURE 45: RELATIVE FRACTION OF TOTAL IMPERVIOUS COVER BY THE FIVE RESIDENTIAL STREET DESIGN COMPONENTS



While street width is important in the creation of impervious cover, a large fraction is produced by other features, such as driveways, sidewalks, and turnarounds. Communities may want to examine subdivision code requirements that influence those features when designing headwater streets.

Benefits of Headwater Streets

Beyond their obvious benefit in reducing site and watershed imperviousness, headwater streets can provide many other environmental and economic benefits. For example, headwater streets:

- Q reduce the amount of clearing and grading needed at the development site
- Q allow for treatment of runoff adjacent to the street
- Q reduce speeds in neighborhoods
- Q make a neighborhood more pedestrian friendly
- Q reduce the capital construction cost
- Q preserve more area for lots
- Q reduce road maintenance costs

Local Experience with Headwater Streets

Most communities in the US have yet to take advantage of the benefits of headwater streets. The gradual evolution in residential street design standards has been well documented by Stabenfeldt (1995) and ULI (1989) and is summarized below:

1. *Most local governments model their residential street design standards after state and/or federal highway criteria, although the traffic capacity and function of their street system is considerably different from highways.* The key reasons for the lack of locally developed residential street designs, according to Stabenfeldt (1995), are perceptions about congestion, emergency access, liability and parking demands. Many local traffic engineers have simply accepted the

notion that wider streets adequately address these concerns, and that wide streets are safer streets.

In most regions of the country, local governments have authority to create narrower design standards for residential streets. Exceptions include a number of states that still retain control over local street design. For example, state oversight or review is still required for local road construction in Connecticut, Montana, North Carolina, Texas and Virginia.

2. *Consequently, very few communities recognize any local road categories that are different from established state and federal street categories.* A recent national survey of counties conducted by the Urban Land Institute (1990) indicated that fewer than half recognize street standards that are substantially different from those of ITE and AASHTO.

3. *Road dimensions have increased sharply over time, indeed, the total width of residential streets has increased by over 50% since the Second World War, in response to concerns about safety, traffic flow, emergency access, spillover parking, more utilities, pedestrian safety, snow removal and liability (ULI 1989).* Traffic engineers have adopted a uniform standard for roads, regardless of the traffic generated by the road. Thus, street function dominates over actual land use as the primary determinant of road type. Experience and common sense, have shown that these concerns can be fully met by narrower streets when traffic volume is light (ULI 1989).

4. *A number of communities have experimented with narrower residential streets, and found them to be an attractive and safe alternative.* These include Bucks County PA, Portland OR, Boulder CO, Dade County FL, Olympia WA and King County WA (ULI 1989; Bray and Rabiner 1991; Fernandez 1994; Wells 1994; and Bucks County 1980). A summary of some of the residential street terminology and geometry that have been used in these communities is provided in Tables 37 and 38, respectively.

Performance Criteria for Headwater Streets

The overall objective for the design of headwater streets is to reduce needless impervious cover while still meeting community needs for safety, traffic flow and parking. Where feasible, headwater streets are also designed to utilize grass channels or swales to maximize pollutant removal and stormwater infiltration. Seven recommended performance criteria for headwater street design are to:

1. Reduce total road length
2. Design narrower headwater streets
3. Limit right-of-way
4. Reduce number and size of cul-de-sacs
5. Limit driveway lengths
6. Design safe pedestrian movement
7. Use open channel stormwater treatment

The performance criteria are intended to be

**TABLE 37: DESIGN STANDARDS FOR HEADWATER STREETS IN THREE LOCAL COMMUNITIES
(SOURCE: STABENFELDT 1995)**

Source/Street Type	Volume (ADT)	Design Speed	Right-of- Way	Pavement Width	Parking	Curb and Gutter
BUCKS COUNTY, PA Access Streets	200	25 mph		16 ft 18 ft 26 ft	none none one side	not required not required required
Residential Subcollector	200- 1,000			20 ft 22 ft 28 ft 36 ft	none none one side both sides	not required required required required
Residential Collectors	to 3,000			20 ft 22 ft	none none	not required not required
Special Purpose Streets/Alleys				12 ft		
BOULDER, CO Access Lane	150	15 mph	28 ft	20 ft	allowed	
Access Street	350	20 mph	48 ft	20 ft 22 ft 26 ft	none one side both sides	required
Residential Street	500- 1,000	25 mph	48 ft	20 ft 26 ft 32 ft	none one side both sides	required
Residential Collector	1,000- 3,000	25 mph	50 ft	22 ft 28 ft 34 ft	none one side both sides	required
Alley			20 ft	18 ft	none	
PORTLAND, OR Through & Cul-de-sac	n.r.	n.r.	35 ft	20 ft	one side	n.r.
Queuing	n.r.	n.r.	40 ft	26 ft	both sides	n.r.

**TABLE 38: HEADWATER STREET CLASSIFICATIONS USED IN THREE LOCAL COMMUNITIES
(SOURCE: STABENFELDT 1995)**

Locality	Street Type/Definition	
Bucks County	<i>Residential Access</i>	Have the sole purpose of providing frontage for service and access to private lots.
	<i>Residential Subcollectors</i>	Are access streets which provide frontage for residential lots and may carry a small amount of through traffic “collected” only from through tributary access streets.
	<i>Residential Collectors</i>	Conduct and distribute traffic between other residential streets of lower order in the streets hierarchy and higher order streets or major activity centers.
Boulder, CO	<i>Access Lane</i>	Designed exclusively for access to a limited number of properties, serving no more than 15 properties.
	<i>Access Street</i>	Provides access to a limited number of properties, serving no more than 25 units.
	<i>Residential Street</i>	Designed to provide access to individual properties and to also provide access to the subcollector and collector.
	<i>Residential Collector</i>	Design to provide access to individual properties and to streets of lower and higher function. They are also designed to accommodate higher traffic volumes with some of the tries using these streets to access the collectors and arterial street network.
Portland, OR	<i>Queuing Street</i>	Intended for two-way traffic; are comprised of a single traffic lane and a parking lane on one or both sides. Queuing streets are possible for both cul-de-sac and through streets.
	<i>Local Traffic Street</i>	Permits two travel lanes plus on-street parking on both sides of the street.

general in nature; communities may choose to develop more specific criteria after analyzing the impervious cover created by their current street classifications and design standards.

Criteria 1. Reduce the total road length needed to serve residential development.

The road network of a residential development should be the shortest possible length needed to serve the total number of dwelling units. Four simple techniques that can be used to create a shorter road network are:

- Q stream protection cluster (cf Chapter 4)
- Q grid or curvilinear road patterns that serve more lots per unit road length than looping or branching patterns
- Q shorter frontage requirements for individual lots (to a minimum frontage distance of 60 ft) also allow more lots to served per unit road length. A small number of flag lots may be permitted if they act to reduce road length as well
- Q shorter centerline radii requirements for road turns. For many headwater streets, a centerline radii of 150 feet is sufficient for safe turning

Criteria 2. Reduce the pavement width of headwater streets that carry less than a thousand ADT and serve less than four dwelling units per acre.

The pavement width of smaller residential streets should be as narrow as possible. Some recommended pavement widths for a range of headwater street sizes are shown in Tables 35 and 38.

Narrower headwater streets typically have one less parking lane and/or moving lane, depending on their traffic volume and on-street parking needs. These narrower streets may occasionally require that one car must pull into a parking lane to let an oncoming car pass. For headwater streets that carry less than 500 ADT, this queuing behavior presents little or no inconvenience to motorists.

Current local street classifications and design standards should be analyzed to identify opportunities for creating narrower headwater streets. The new design standards will undoubtedly vary somewhat from one locality to another, based on such factors as residential parking demand, lot size, curb and gutter requirements, design speeds, emergency access and snow storage.

Criteria 3. Make right of way requirements only as wide as needed to accommodate structures that are actually built on each side of the street.

Since most headwater streets will never be widened in the future, a narrower right of way of 8 to 15 feet on each side of the street can be easily justified. A narrower right of way can reduce the need for tree clearing or grading. In most cases, the right of way should include (from the pavement edge outward): a 3 to 5 foot wide grass strip, a four foot wide sidewalk, and an extra foot of grass. Utilities and storm drains are located underneath the street or within the right of way. Some other considerations to keep in mind when setting right of way include:

- G** If utility corridors or sidewalks are installed on only one side of the street, the right of way should be reduced proportionately.
- G** A wider right of way may be needed for grass channels or swales
- G** Clearing of trees within five feet of the pavement edge should be avoided in forest areas, wherever possible
- G** In snow regions, the grass strip area in the right of way may need to be increased to 6 to 8 feet for storage of plowed snow

Criteria 4. Reduce the use and effective radius of cul-de sac turnarounds

Large cul-de-sacs are expensive, unattractive, and create needless impervious cover. Their use should be discouraged. Since headwater streets are located at the end of the road network, the primary design objective is to get direct emergency access to homes. To turnaround and go back, however, may occasionally require a two point turn. Thus, for most headwater streets serving less than 25 homes, a minimum cul-de-sac open turnaround radius of 30 feet is recommended. A landscaped donut can be placed in the center of the cul-de-sac turnaround as long as it maintains an internal turning radius of 17 to 20 feet.

Alternative turnarounds, such as the T-shaped “hammerhead,” create less impervious cover than any circular option, and should be encouraged in shorter cul-de-sacs, particularly in rural areas.

Criteria 5. The length of driveways should be limited to satisfy residential parking demand and access requirements.

As noted earlier, driveways generate a surprisingly large fraction of the impervious cover created by a residential street. Driveway length can be limited to 30 to 40 feet in most large lot residential lots that have two car garages, and still fully meet residential parking demand. The key site design parameter that influences the length of driveways; however, is the mandatory front yard setback to the home. Local codes should be reviewed to determine if excessive setback requirements of 60 to 75 feet can be modified to accommodate shorter driveways. Some other techniques for reducing the impervious cover created by driveways include:

- G** shortening the minimum driveway width from 20 to 18 feet.
- G** limiting impervious surfaces to two tracks, with the remainder of the driveway in grass or pervious surface
- G** utilizing a shared driveway to connect 3 or 4 units together (rather than a wider road)

Criteria 6. Design for safe pedestrian movement through the community

Safe pedestrian movement does not always entail wide sidewalks on both sides of the street. Indeed, many adults and children still move through a community along the street, even when sidewalks are available. The key safety consideration is that headwater streets have both low traffic speeds and good visibility. If these considerations are met, it is possible to relax the double-wide sidewalk

requirement. For example:

- G sidewalks can be located on only one side of the street
- G sidewalks can be replaced by walkways located within community open space and away from streets
- G the width of sidewalks can be as narrow as four feet
- G sidewalks should be graded so that stormwater runoff travels to the front yard and not into the street

Criteria 7. Wherever possible, the right of way of headwater streets should be utilized for the treatment of stormwater quality using open grass channels.

Headwater streets provide engineers with an ideal location for effectively treating the quality of stormwater runoff near its source. The basic technique is to design an open, vegetated channel within the right of way (and eliminate curb and gutters).

In general, road designers should have to demonstrate that open channels are *not feasible* on each headwater street before any curb and gutter are accepted. The following conditions are evidence that a headwater street cannot support an open channel:

- G longitudinal slopes greater than 5%
- G computed runoff velocities for the two year design storm event that exceed the critical erosive velocity of 4 to 5 feet per second
- G local climate or soils make it impossible to establish dense turf throughout the year
- G presence of the water table within a foot below the proposed channel bottom,

- G or a housing density exceeding 3 dwelling units per acre

Headwater Street BMPs

If an open channel remains feasible for the site, designers can use one of four open channel designs for runoff treatment—drainage channels, grassed channels, dry swales and wet swales (see Figure 36). Some design guidance on each design option are outlined below:

a. Drainage Channels

This form of open channel is solely designed to have enough capacity to safely convey runoff from large storm events without erosion. The channel cross-section has a hydraulic capacity to handle the peak discharge rate for the ten year storm event, and channel dimensions (i.e., slope and bottom width) are carefully selected so that the critical erosive velocity is not exceeded during the peak discharge rate for the two year storm event. Since drainage channels are not explicitly designed to treat runoff from more frequent storm events, they provide only limited water quality benefits, unless soils are extremely sandy (MWWOG 1983). Consequently, the use of drainage channels is primarily restricted to *runoff pretreatment* (i.e., trapping coarse sediments in the channel before they are delivered to a downstream pond, wetland, filter or infiltration facility).

b. Grass Channels

Grass channels are different from drainage channels in that they are designed to meet runoff velocity targets under three storm conditions—a water quality design storm, the two year design storm and the ten year design storm (see Figure 46). In addition, the total

length of the channel must provide at least ten minutes residence time for the water quality storm. In some regions of the country, grass channels are termed “biofilters” (Seattle METRO 1992). To meet these criteria, grass channels have broader bottoms, lower slopes and dense vegetation. Performance monitoring has shown that grass channels are more a reliable technique for removing pollutants from stormwater than drainage channels. Reasonably high removal rates have been

reported for sediment and hydrocarbons. Grassed channels, however, have proven to be less effective in removing soluble nutrients, soluble metals or bacteria. In addition, field assessments indicate that many grassed channels are not constructed to specification, lack dense vegetation or have standing water (Horner 1988), and may not be suitable for all residential sites. Thus, while grass channels may satisfy local requirements for stormwater quality treatment, they need to be carefully constructed, inspected and maintained. Some general guidance on grass channel design can be found in Table 39, and detailed design methods are provided in Seattle METRO 1992, and Claytor and Schueler 1995.

FIGURE 46: SCHEMATIC OF A GRASSED CHANNEL

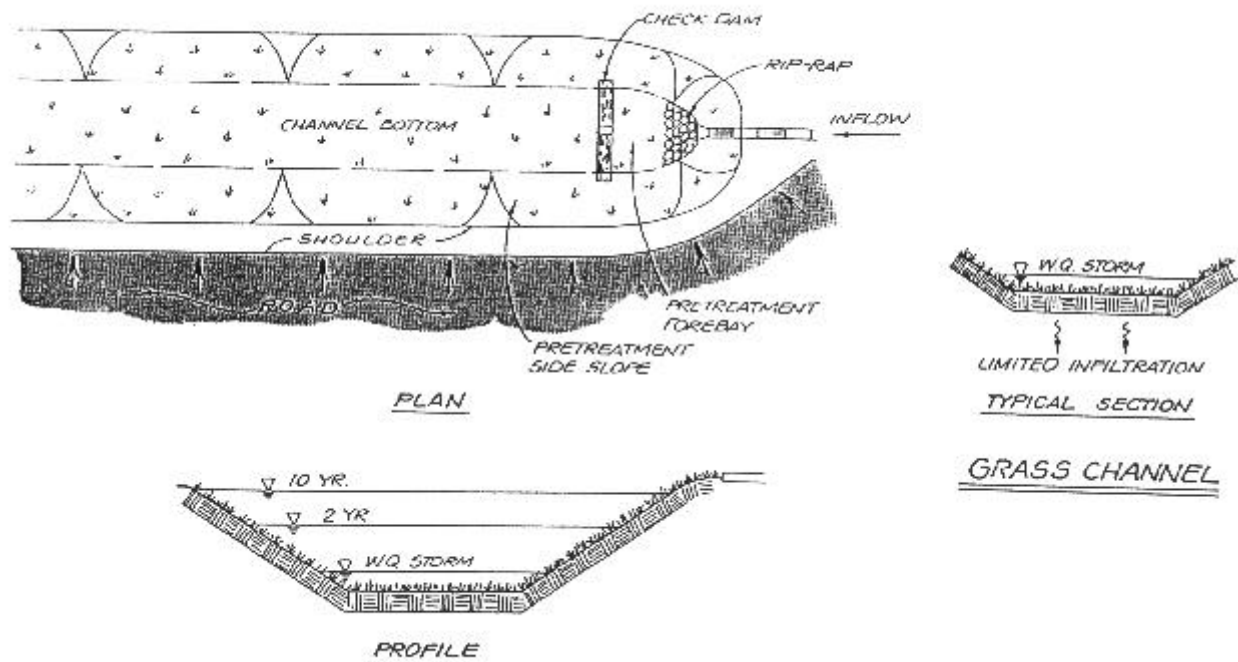


TABLE 39: DESIGN GUIDANCE FOR BIOFILTER SWALES (ADAPTED FROM HORNER 1988, REEVES 1995)

Geometry: Preferred geometry minimizes sharp corners and has gentle slopes, parabolic or trapezoidal shapes, with sideslopes no greater than 3:1 (h:v).
Longitudinal Slope: Should be in the range of 2 to 4%. Checkdams should be installed if slopes exceed 4% and underdrains installed if slopes are less than 2%.
Swale Width: Should be no wider than 8 feet, unless structural measures are used to spread flow.
Maximum Residence Time: Try to achieve a hydraulic residence time for the 6 month 24 hour storm of about 9 or 10 minutes.
Maximum Runoff Velocity: no more than 0.9 fps for 6 month, 24 hour storm, and 1.5 fps for 2 year storm event.
Manning's <i>n</i> Value: Recommend the use of a 0.20 value in design.
Grass Height: Normal grass height should be at least two inches above design flow depth.
Mowing: Routine mowing is used to keep grass in active growth phase, and to maintain dense cover.
Biofilter Soils: A sandy loam topsoil layer, with an organic matter content of 10 to 20%, and no more than 20% clay. If soil test indicates that the current soil does not meet these criteria, a surface layer topsoil amendment may be used.
Water Table: Designer should check to determine the level of the seasonally high water table. If it is within a foot of the bottom of the biofilter, it may be advisable to select wetland species.
Plant Selection: Select grass species that produces a uniform cover of fine-hardy vegetation that can withstand the prevailing moisture condition. Wetland adapted species such as <i>Juncus</i> and <i>Scirpus</i> may be utilized if drainage is poor.
Landscaping: Other plant material can be integrated into a biofilter; but care should be taken to prevent shading or leaf fall into swale.
Construction: Use of manure mulching or high fertilizer hydroseeding to establish ground cover should be avoided during construction, as these can result in nutrient export.

c. Dry Swale

Dry swales are designed to completely store the runoff volume from the water quality storm event and filter it through 30 inches of swale soil before it is collected by an underdrain (Fig. 47). Consequently, dry swales are expected to have the highest removal rates of any open channel system (Yousef et al. 1985, and Harper 1988). To achieve such rapid rate of infiltration, it is often necessary to modify the parent soils to improve their infiltration rate and/or to allow up to 18 inches of temporary ponding above the swale. Some other key design criteria for the dry swale include:

G Pretreatment is required to protect the swale. For pipe inlets, 0.1 inch per contributing acre should be temporarily

stored behind a checkdam. For lateral inflows, gentle slopes or a pea gravel diaphragm can be used.

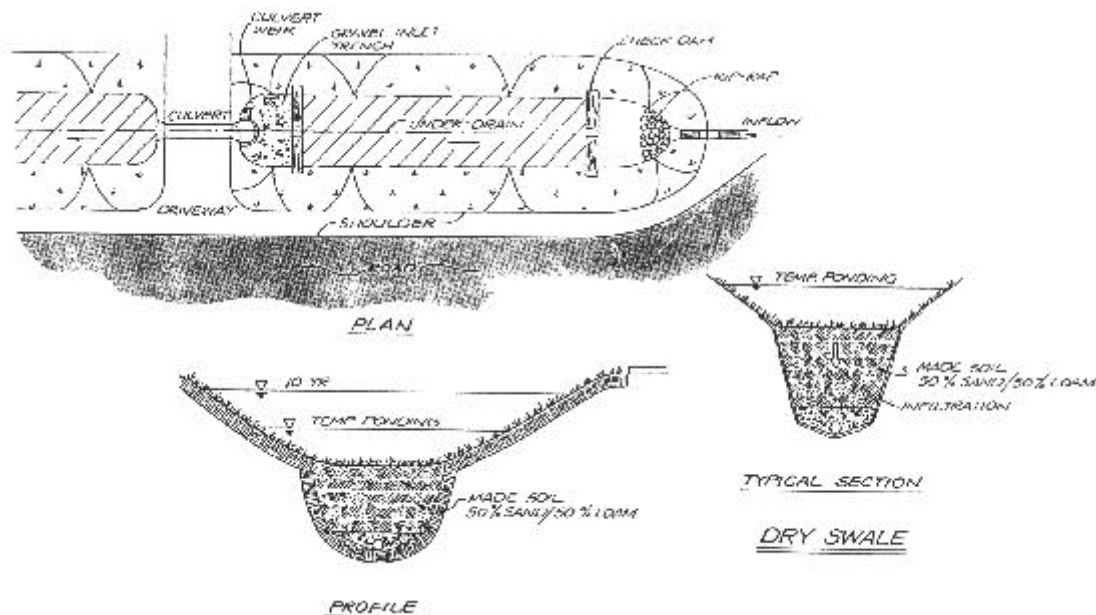
G Swales include a prepared soil filter bed that is 30 inches deep and composed of 50% sand and 50% silt loam.

G Swale filter beds are drained by a longitudinal perforated pipe to keep the swale dry after storm events.

G Swales are parabolic or trapezoidal shapes, with gentle side-slopes (no greater than 3:1 h:v), and bottom widths ranging from 2 to 8 feet.

G Geotechnical tests are required to determine the location of the water table.

FIGURE 47: SCHEMATIC OF A DRY SWALE



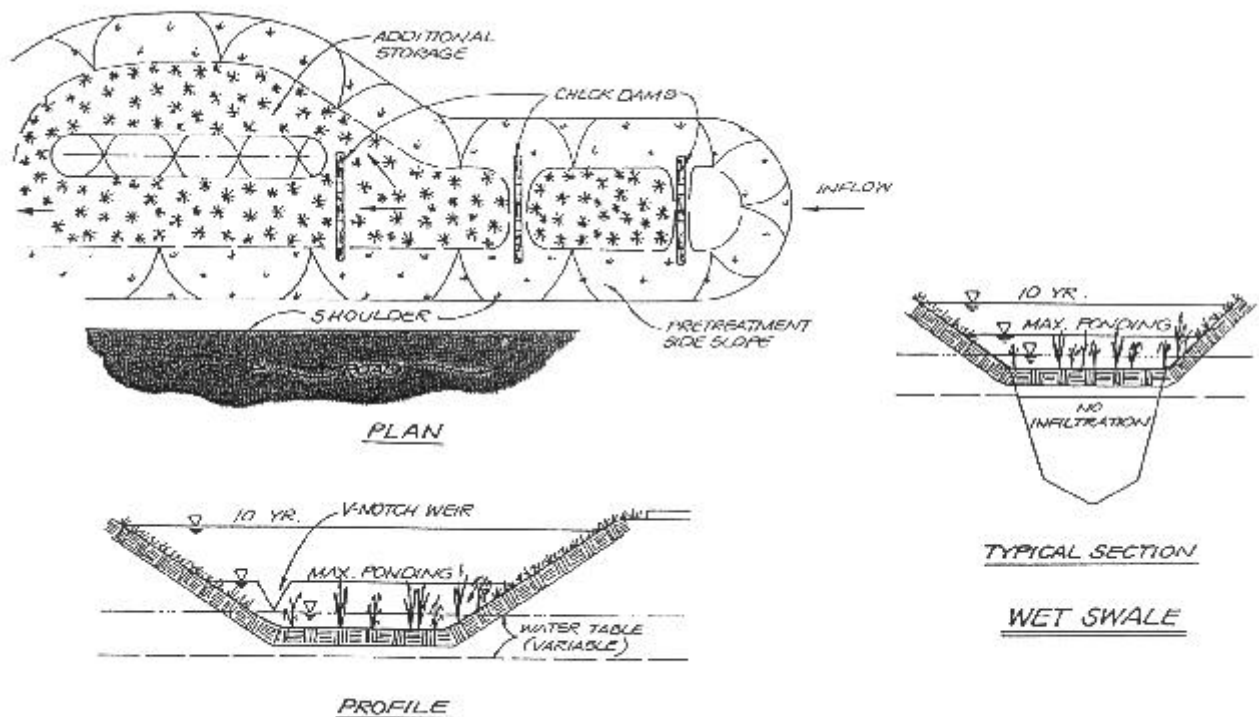
The dry swale is the preferred open channel option for most residential settings since it is designed to prevent standing water problems that generate homeowner complaints. The swale is designed to rapidly dewater, thereby allowing front yards to be easily mowed. Design methods for dry swales can be found in Claytor and Schueler (1995).

d. Wet Swales

In some regions of the country, the water table is located very close to surface. When swales are excavated in these regions, it is likely that soils will be fully saturated, or standing water will be present in the swale during all or part of the year. The best

design in these situations is the wet swale (Figure 48), which essentially acts as a very long and linear pocket wetland. Monitoring studies in Florida indicate that wet swales can have reasonably high pollutant removal rates (Yousef et al. 1985 and Harper 1988). It should be clearly noted that wet swales are often not appropriate in many residential settings, as the public seldom accepts standing or stagnant water in their front yards. Application of wet swales is thus limited to large lot rural developments, and headwater street sections that do not front individual lots. Design methods for wet swales, including wetland plant selection, can be found in Claytor and Schueler (1995).

FIGURE 48: SCHEMATIC OF A WET SWALE



Runoff Treatment Options for Enclosed Storm Drain

If open channels are not a feasible drainage option for a headwater street, then stormwater quality treatment must be provided within the storm drain network (in-line treatment) or at the outfall of the storm drain (end-of-pipe treatment).

The in-line treatment strategy involves trapping sediments within special structures within the storm drain network. These underground structures include inlets, catchbasins, sump pits or oil/grit separators. As a general rule, these structures often have limited storage capacity compared to the large flow rates they must handle during intense storm events. Consequently, pollutants trapped within the structures during smaller storm events often are resuspended during larger ones. Pollutant storage is temporary, and good removal rates can only be achieved when pollutants are physically removed on a frequent basis. Recent research has demonstrated that trapped pollutants must be cleaned out almost monthly if meaningful pollutant reduction is expected (Mineart and Singh 1995, Schueler and Shepp 1993). Local public works departments should carefully evaluate whether they have adequate budgets and staff to perform frequent cleanouts before accepting in-line treatment options.

The end-of pipe strategy has been the most common approach for treating the quality of street runoff. Runoff is rapidly delivered to a downstream point where it is treated in a large stormwater pond, wetland or filtering system.

Resources Needed for Implementation

A great deal of local inertia must be overcome to modify existing residential street design standards. The greatest barrier to realizing headwater streets are often local highway, public works and fire department personnel who may be reluctant to change the way things have always been done. Consequently, it is often necessary to create an interagency task force that includes each agency to oversee the development of revised residential street designs. Through this outreach process, many communities have found more common ground than they had expected (Wells 1994). Once agreement has been reached, headwater street standards will still need to be formally adopted in subdivision codes or ordinances, following a local public involvement plan.

References

- AASHTO. 1990. A Policy on Geometric Design of Highways and Streets. Washington, DC. 46 pp.
- Arendt, R. 1994. Rural by Design—maintaining small town character. American Planning Assoc. Washington, DC. 460 pp.
- Bannerman, R. 1994. Sources of Urban Stormwater Pollutants Defined in Wisconsin. *Wat. Prot. Techniques*. 1(1): 30–32.
- Bucks County Planning Commission. 1980. Performance Streets—a concept and model standards for residential streets. Bucks County, PA. 46 pp.
- Bray, T and K. Rabiner. 1991. Report on New

- Standards for Residential Streets in Portland, Oregon. Bureau of Transportation Engineering. Portland, Oregon.
- Carrol County, 1992. Design Manual-Roads and Storm Drains. Dept. Of Public Works. Book No. 0190. Bureau of Engineering. Carrol County, MD.
- Claytor, R. and T. Schueler. 1995. Design of Stormwater Filtering Systems. Chesapeake Bay Research Consortium. Center for Watershed Protection, Silver Spring, MD 202 pp.
- Dorman et al. 1989. Retention/detention and overland flow for pollutant removal in highway runoff. FHWA/RD – 89/202 pp
- Federal Highway Administration. 1990. Pollutant Loadings and Impacts from Highway Stormwater Runoff. FHWA–RD88–006. Washington, DC. 440 pp.
- Fernandez, J. 1994. Boulder Brings Back Neighborhood Streets. *Planning*. 60(6): 21–26.
- Harper, H. 1988. Effects of Stormwater Management Systems on Groundwater Quality. Final Report. Environmental Research and Design, Inc. Florida Dept. of Environmental Regulation. 460 pp.
- Homer, R. 1988. Biofiltration systems for storm runoff water quality control. Washington Dept. of Ecology. 84 pp.
- Institute of Transportation Engineers. 1987b. Trip Generation Rates Washington, DC.
- Institute of Traffic Engineers. 1991. Residential Street Design Guidelines– recommended practice. Washington, DC. 68 pp.
- Metropolitan Washington Council of Governments. 1983. Final Report. Nationwide Urban Runoff Project. Department of Environmental Programs. US EPA. Washington, D.C. 222 pp.
- Mineart, P and S. Singh. 1995. The value of more frequent cleanouts of storm drain inlets. *Wat. Prot. Techniques*. 1(3): 129–130.
- Oberts, G. 1994. Influence of Snowmelt Dynamics on Stormwater Runoff Quality. *Wat. Prot. Techniques*. 1(2): 55–61.
- Reed, C. 1991. Subdivision Development and Construction Standards. Part 1: Street ROW and Cross Sections. The Zoning Report. 9(14):1–8.
- Reeves, E. 1995. Performance and Longevity of Biofilters in Washington, *Wat. Prot. Techniques* 1(3): 117–120.
- Santa Clara Valley NPS Program. 1994. Cars are Leading Source of Metal Loads in California. *Wat. Prot. Techniques*. 1(1): 28.
- Schueler, T. and D. Shepp, 1993. The quality of trapped sediments in oil grit separators in suburban Maryland. MWCOG. MDE. Washington, DC. 88 pp.
- Seattle METRO. 1992. Biofiltration swale performance: recommendations and design considerations. Publication No. 657. Washington Dept. Of Ecology. 220 pp.
- Stabenfeldt, L. 1995. Residential street strategies for urban watersheds. Environmental Land Planning Series. Metropolitan Washington Council of Gov'ts. US EPA. Washington, DC. 66 pp.
- US Environmental Protection Agency. 1983. Results

of the National Urban Runoff Monitoring Project.
Washington, DC.

Urban Land Institute, 1989. Survey of Residential
Street Design. ULI. Washington, DC. 78. pp.

Urban Land Institute. 1990. Residential Streets.
(second edition). American Society of Civil

Engineers and National Association of
Homebuilders.106 pp.

Wells, C. 1994. Impervious Surface Reduction
Study. Draft Report. City of Olympia Public Works
Department. Washington Department of Ecology.

182 pp..

Williams, K, T. McCauley and M. Wyckoff. 1990.
Land division and access controls. Planning and
Zoning Center. Michigan Society of Planning
Officials, Lansing, MI.76 pp.

Yousef, Y., M. Wanielista, H. Harper, D.
Pearce and R. Tolbert. 1985. Best
Management Practices – removal of highway
contaminants by roadside swales. Final
Report. University of Central Florida. Florida
Dept. Of Transportation. 166 pp.